

NONDESTRUCTIVE RESIDUAL STRESS MEASUREMENTS IN RAILROAD WHEELS USING THE LOW-FIELD MAGNETOACOUSTIC TEST METHOD

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INTRODUCTION

Residual tensile stresses in the rims of railroad wheels created by repeated applications of brakes have been known to contribute to catastrophic wheel failures. About 235,000 potentially dangerous railroad wheels are being removed annually in the US to prevent the wheel-related accidents [1]. The current industrial standard determining the removal of a particular wheel from service is the federal regulation of a visual inspection method. In this method one determines the width of a discolored band in the rim of a wheel radially, and if the width exceeds 10 cm (4 in.) the wheel is considered potentially dangerous. Destructive test methods, e.g., hole-drilling and saw-cutting techniques, however, have shown that the visual inspection method is unreliable. Some wheels considered dangerous had no appreciable residual tensile stresses, while some considered safe (not discolored) had dangerous level of residual tensile stresses in the rim when saw-cut or hole-drilled. To improve the level of safety in railroad transportation and reduce waste, reliable NDE methods have been in great demand.

Several ultrasonic and magnetic NDE techniques, such as acoustic birefringence, acoustic velocity and Barkhausen noise, have been available for bulk stress characterization in steel [2,3,4]. The weaknesses of these techniques are their sensitivity to many material properties other than just the stress state, which makes interpretation of results extremely difficult. In an effort to overcome such a barrier to reliable wheel safety inspections and general residual stress-related problems in steel, a new approach has been proposed utilizing the magnetoelastic properties.

The low-field magnetoacoustic technique has been the focus of the development for railroad wheel residual stress measurements. The laboratory experimental results have shown that the sign of residual stress can be determined without necessitating calibration standards. It is also expected that the magnitude of residual stress can be

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estimated with the provision of calibrated data for particular types of samples. This paper reviews the low-field magnetoacoustics technique and initial results for two railroad wheels with the different signs of residual stress states, as determined by saw-cutting technique.

LOW-FIELD MAGNETOACOUSTIC TECHNIQUE

The term "magnetoacoustic interaction" covers general phenomena that involve changes in acoustic properties due to an externally applied magnetic field. Three different types of magnetoacoustic interaction exist. In nonmagnetic materials at low temperature, a strong external magnetic field causes changes in acoustic wave velocity and attenuation. These changes are an oscillatory function when plotted against inverse magnetic field [5]. The origin of such behavior has been explained properly in terms of quantum mechanics. In ferromagnets the magnetoacoustic interaction has been observed commonly with magnetic field strong enough to bring the sample to the pure para-process region, i.e., far beyond the technical saturation point [6]. Changes in acoustic properties in this region occur due to forced magnetostriction and accompanying physical processes. The earliest discovery of magnetic field-dependent elastic and, consequently, acoustic properties in ferromagnets, however, was made with net induced magnetization below the saturation point and is known as the ΔE -effect [7,8]. The acoustic responses related to the ΔE -effect observed in the low external field region directly relate to stress states in ferromagnets.

The ferromagnetic and lattice systems are related to each other by the magnetoelastic interaction [9]. A well known example is the macroscopic dimensional change in a ferromagnet with the application of a relatively small magnetic field. This is a direct evidence that the lattice unit cells are anisotropically deformed in the ferromagnetic state and this is called spontaneous magnetostriction. Further deformation of the lattice by stress will affect the ferromagnetic system through the magnetoelastic interaction [7,8].

Two important phenomena based on the magnetoelastic interaction are the stress-induced domain alignment and domain structure-dependent elastic modulus of a ferromagnet. Two types of domain walls exist in iron: 90- and 180-degree domain walls. It can be shown that only 90-degree walls move in response to uniaxial stress, such that domains align parallel to the tensile stress axis and perpendicular to the compressive stress axis [7,8]. The application of uniaxial stress induces pure elastic strain and magnetoelastic strain whenever the stress-induced domain wall motion is possible. The sign of magnetoelastic strain can be proven to be the same as that of elastic strain and in case of iron the presence of 90-degree walls should lower the elastic modulus. All these facts are also applicable to iron base alloys provided their domain structures and the signs of spontaneous magnetostriction remain the same as those of pure iron.

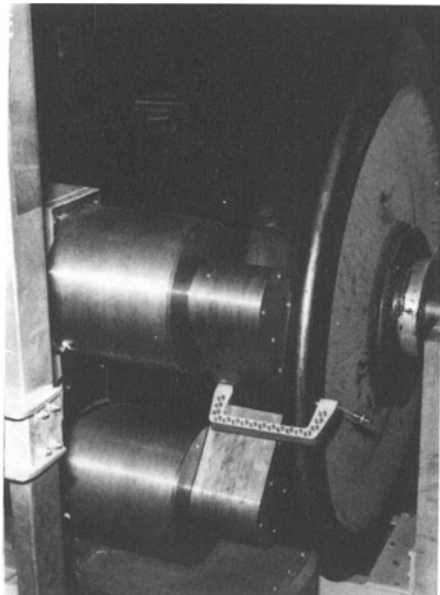
Ferromagnetic domain walls interact with lattice defects through local lattice strain fields they create. Hence during the process of domain wall motions, lattice defects either repel or attract the domain walls, depending on particular situations. Local lattice strain fields of 90-degree walls are stronger and longer ranged than those of 180-degree walls. It is known that the mobility of 90-degree walls is lower than that of 180-degree walls of iron roughly by a factor of 50 [10]. This causes the main difficulty of complete stress-induced domain alignment in impure ferromagnets and there always exists a fraction of energetically unfavored domains in steel samples, even under a very high

uniaxial stress. These residual domains either disappear or grow during field-induced domain wall motion depending on the orientations of uniaxial stress and applied-field axes.

Laboratory experiments have shown that the acoustic natural velocity decreases until domain wall motion is completed in steel samples magnetized in the compressive stress axis [11]. A definite minimum point always exists in the curve as natural velocity begins to increase due to domain rotation. The negative slope of the natural velocity curve in this case enables to detect the presence of uniaxial compressive stress without being assisted by any calibration standard. While such an effect of uniaxial compressive stress has been proven to be general, the shape of natural velocity curves differ in different types of steel [12]. Hence the stress amplitudes cannot be estimated by this technique alone.

TEST SETUP AND INSTRUMENTATION FOR RAILROAD WHEELS

The test setup consists of three major parts: magnet system, acoustic measurement instruments, and control computer. Fig. 1 (a) and (b) show the magnet for magnetization parallel to the circumferential axis of railroad wheels and the computer-controlled data acquisition system, respectively. Low carbon steel (1018 steel) is used for the core and end poles. The bottom of rotatable end pole pieces were machined to fit to the rim surfaces of 36 in. diameter wheels, but several inches of wheel diameter variation does not cause a significant gap between the poles and wheel surface. The cross-sectional area of the poles and core were chosen such that more than 95% of the total Ampere-turns of potential drop occurs across the portion of the rim to be magnetized. Each water-cooled electromagnet has 275 turns with total resistance of



(a)



(b)

Fig. 1. (a). Steel-core electromagnet for magnetization parallel to the circumferential axis. (b). Computer-controlled data acquisition system.

2.1 Ohms. Assuming a parallelopiped region of magnetization in the rim area, a maximum 10 Amperes of current in the magnet produced magnetic induction close to saturation. Demagnetization after each measurement was performed by following about 40 minor hysteresis loops with the maximum field at each loop decreased exponentially.

A pulsed-phase-locked-loop (P^2L^2) acoustic interferometer was used to measure the small changes in acoustic wave velocity. The fractional change in acoustic natural velocity is defined as:

$$\frac{\Delta W(B)}{W} = \frac{\Delta V(B)}{V} - \frac{\Delta L(B)}{L}$$

where B is magnetic induction, V is the acoustic phase velocity and L is the acoustic path length. It can be shown that the fractional change in natural velocity is identical to the fractional change in frequency of a phase-locked acoustic wave. The fractional change in path length in this case is due to magnetostriction and its contribution is negligible. The acoustic frequencies are directly read by a frequency counter and transferred to the computer. The proven resolution of fractional frequency measurement by the P^2L^2 is less than 1 PPM and details of this instrument can be found elsewhere [13].

EXPERIMENT WITH RAILROAD WHEELS AND RESULTS

Two railroad wheels used in this experiment were already saw-cut tested at AAR (Association of American Railroads) before they were delivered to NASA. One of these two was almost new but removed from service due to mechanical damage on the tread surface. The gap in the rim of this wheel opened, indicating residual tensile stress prior to saw-cut testing. The other one has been in service for a long period of time, as evidenced by severely worn rim. The rim of this wheel, however, closed when saw-cut testing was performed. It is believed that residual stresses of the same signs still remain in these wheels even though the magnitude and stress distribution have been modified in the vicinity of the saw-cuts.

Through out the experiment, the magnetic field was applied parallel to the rim axis and 5 MHz compressional waves were propagated through the rims (perpendicular to the hoop axis) in the pulse-echo mode. The difficulty in presenting the results in this case was choosing a physical parameter indicating the degree of magnetization in the region of acoustic wave propagation. Apparently, the total magnetic flux in the core should be measured to calculate magnetic induction at a desired location in the wheel. This, however, is only possible when the flux distribution is known, for example, by finite element calculations. Such computational work was not included in the present stage and the remaining variable to monitor was the current applied to the electromagnet to which the internal magnetic field is proportional. As long as a significant demagnetization field is not present due to air gaps, this proportionality is guaranteed.

Fig. 2 shows the fractional frequency shift ($\Delta f/f$) as a function of current applied to each electromagnet for the "open saw-cut" wheel with magnetization parallel to the rim axis. The label at the end of each $\Delta f/f$ curve indicates the position of the ultrasonic transducer with respect to the saw-cut location. According to the tests performed on medium range carbon steels, tensile stress causes an upward shift of the

$\Delta f/f$ curve from the unstressed curve [12]. As shown in the figure, the curve obtained at a position exactly opposite to the saw-cut location indicates the highest level of residual tension. This is consistent with assumption that the residual stress should remain high at a point far from the location of saw-cut. The considerably lower position of 90-degree curve compared to those of 270- and 285-degree position is not readily explainable. It is possible that the distribution of residual stress throughout the hoop was asymmetric.

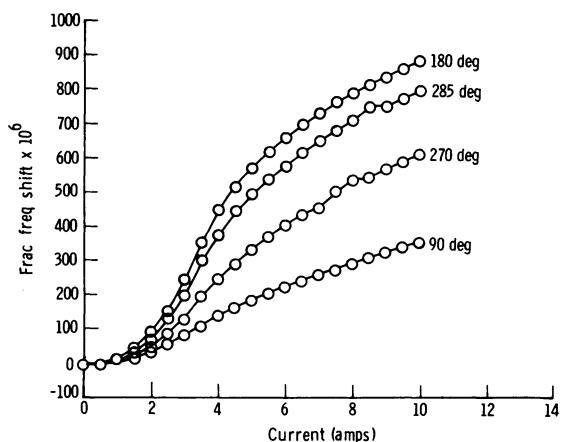


Fig. 2. $\Delta f/f$ curves in the "open saw-cut" wheel obtained at various angular positions with respect to the "saw-cut" location.

The "closed saw-cut" wheel was measured during this initial test at only one position approximately opposite to the saw-cut location. Fig. 3 shows the $\Delta f/f$ curve for the "closed saw-cut" wheel, which contained residual compressive stress, compared with the 180-degree curve in Fig. 2. This comparison between the two wheels clearly shows the difference in the signs of residual stresses.

Rather peculiar behaviors of $\Delta f/f$ were also observed in the "closed saw-cut" wheel. During the process of repeated measurements to assure the reproducibility, this particular wheel had shown a significant time dependent effect. While it has been proven for many laboratory samples and other railroad wheels, that $\Delta f/f$ curves were always reproduced, such was not the case for this wheel. In Fig. 4 the curve labelled "near tests" represents the results of several measurements at the initial stage of testing. As the measurements were repeated, the curve slowly began to rise and, after about ten measurements, this upward shift leveled off producing the curve labelled "retest". It was then found that the original curve could be reproduced only when the wheel was left undisturbed at least for several hours. Such measurement cycles were repeated many times, and the original curve was reproduced whenever sufficient relaxation time was allowed. These are shown by the curves labelled "later tests" and "last test".

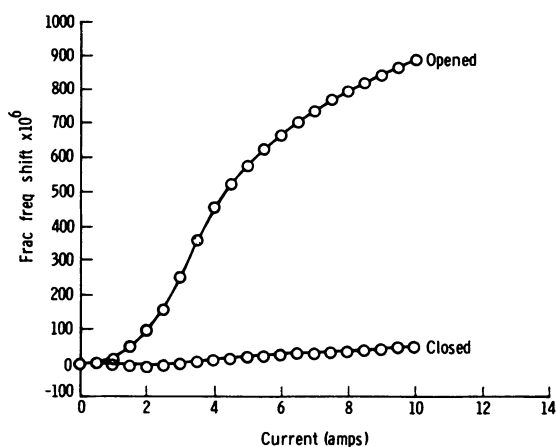


Fig. 3. Comparison between the "open saw-cut" and "closed saw-cut" wheels. Both curves were taken at a position opposite to the saw-cut location. Measurements were possible at only one position in the "closed saw-cut" wheel due to wear in the rim.

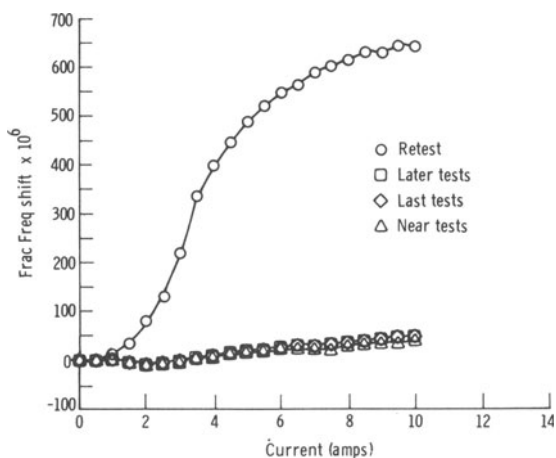


Fig. 4. Time dependence of $\Delta F/F$ in the "closed saw-cut" wheel. Repeated cycle of measurement and demagnetization caused upward shift of the $\Delta F/F$ curve which leveled off at the top curve. After several hours of relaxation, the original curve was reproduced (three curves at the bottom).

DISCUSSION

The unusual time dependence of the $\Delta f/f$ curve discovered in the "closed saw-cut" wheel is not a surprise when one considers the magnetic after-effect caused by interstitial impurities. In the present case, the interstitial impurities are carbon atoms believed to occupy the octahedral sites of body-centered-cubic (BCC) unit cells of iron. Due to magnetostriction, these unit cells in the ferromagnetic state are, however, slightly tetragonal with the longer axis oriented parallel to

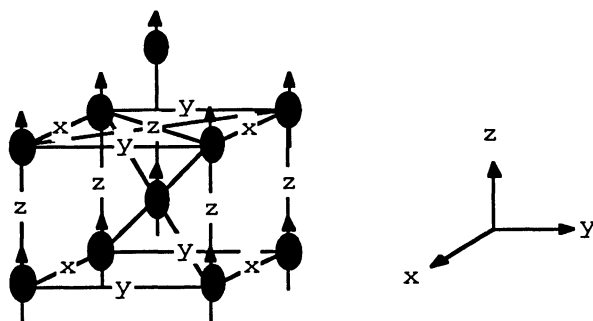


Fig. 5. Octahedral interstitial sites in a body-centered-cubic unit cell. Each site is labelled according to the orientation of the tetragonal axis.

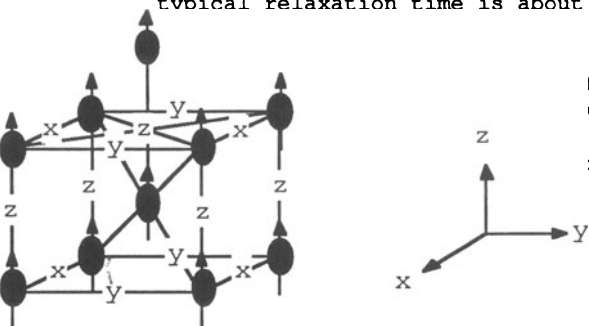
the domain magnetization vector as shown in Fig. 5. The Gibbs type free energy at the x and y sites (G_x and G_y) must be the same, while they differ from that at the z sites (G_z). According to experiments by de Vries et. al, the x and y sites are energetically more favored than the z sites, i.e., $G_z > G_x$ or G_y [14]. Hence, at the thermal equilibrium, the ratio of site occupational probabilities can be expressed as:

$$\frac{P_{x,y}}{P_z} = \frac{\text{Exp}(-G_z/kT)}{\text{Exp}(-G_x/kT)} > 1$$

where k is the Boltzman constant and T is the sample temperature in Kelvin.

When the orientation of the domain magnetization vector is suddenly changed, the equilibrium distribution of impurities among the sites is disturbed and the system begins to change toward the new equilibrium state. Since thermodynamical descriptions are not possible for a system in an inequilibrium state, the rate of transition between two equilibrium states has to be determined experimentally.

The rate of transition was measured by Gersdorf and de Vries, using a slightly textured polycrystalline iron disk containing 0.015 wt.% of interstitial carbon [15]. Their sample had two magnetically easy axes, perpendicular to each other, in the disk plane. After keeping the disk saturated in one of the easy axes for a long time, they suddenly rotated the sample by 90 degrees and let the disk oscillate about the magnetic field axis. The time dependence of the period of oscillation after the sudden rotation of the sample is the direct measure of the transition rate (or the relaxation time). This is because the torque applied to the disk during the oscillation is proportional to the magnetic anisotropy induced by the distribution of interstitials obtained previously by saturating the disk in the other direction. As shown in Fig. 6, the twoval relaxation time is about 90 minutes, but it takes about five



te the transition between the two
ve agrees well with the time needed to
the observing the "retest" curve in
question; "why $\Delta f/f$ should be much higher

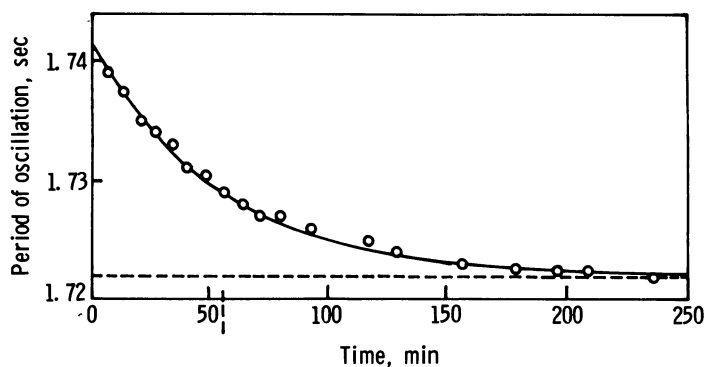


Fig. 6. Time dependence of the period of oscillation of a polycrystalline iron disk due to carbon diffusion. (Reproduced from Ref. 16).

in the 'retest' state than in the other states?". A partial answer can be provided by the concept of elastic dipoles of point defects.

Local strain fields are created by lattice defects. Such strain fields (or force fields) can be expressed in multipole expansion in the case of point defects and the dipole term dominates when the strain fields interact with external influences [16]. This is similar to the interaction between an electric dipole and field, and the term "elastic dipole" can be defined from the interaction [17]. In terms of lattice strain near a point defect in solids, it is sufficient to consider the strain induced up to the second nearest neighbor host atoms around the defect. Fig 7. shows the displacements of the first and second nearest host atoms due to an impurity at the octahedral site. A typical value of strains are about 7% and 1% for the first and second nearest neighbors, respectively [18]. Such strain fields associated with elastic dipoles are believed to affect acoustic wave propagation even though these strain fields are fairly localized.

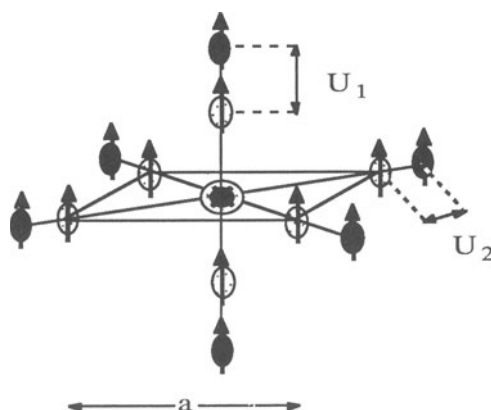


Fig. 7. Displacement of first and second nearest host lattice atoms due to an octahedral interstitial.

The "closed saw-cut" wheel was examined to determine if a correlation existed between the microstructure of steel in this wheel and that of polycrystal iron samples. As mentioned previously, this wheel was removed from service due to wear. The general surface corrosion of this wheel was such that the identification markings, which would normally have been used to determine the processing history of the wheel, were illegible. Laboratory metallurgical techniques were therefore needed to determine the structural properties of this sample.

The wheel in question exhibited a mixed microstructure of ferrite and pearlite (a lamellar structure of carbide and ferrite). It was also determined that this wheel was a cast component, as evidenced by pronounced dendritic formation at the rim portion of the wheel. That is, the steel in the rim of the wheel solidified in such a manner that migration of carbon atom cloud conceivably have occurred, creating adjacent area of low carbon-bearing ferrite. While firm evidence is not immediately available to substantiate further speculation concerning the magnetic properties of this particular wheel, it is postulated that the microstructure of this sample was such that the magnetic after-effects discussed above were to be manifested in our testing. That is, repeated testings caused alignment of the elastic dipoles of carbon which was not fully erased during the demagnetization process.

CONCLUSION

This paper reviews the development of the low-field magnetoacoustic stress technique and introduces the prototype setup designed for whole railroad wheel testings. The initial test results with the setup show agreements with the results for laboratory samples. A time dependence in $\Delta f/f$ was discovered in a cast steel wheel and a qualitative analysis is given on the basis of magnetic after-effect.

ACKNOWLEDGEMENT

This work was supported by the Federal Railroad Administration and by NASA, through the Technology Utilization Program. Authors wish to thank P. W. Kushnick for his direct contribution with instrument building, and J. S. Heyman, D. H. Stone and G. E. Stevens for their support to this project.

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